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FINAL REPORT

FABRICATION OF GRAPHITE/EPOXY CASES FOR ORBIT INSERTION MOTORS

SUBMITTED TO

JET PROPULSION LABORATORY
ON JPL CONTRACT 953210

BY

BRUNSWICK CORPORATION
Technical Products Division
4300 Industrial Ave.
Lincoln, Nebraska 68504

Prepared by W. W. Schmidt

AUGUST 20, 1973

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

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ABSTRACT

This report describes the fabrication procedures for filament-wound rocket motor cases, approximately 26.25 inches long by 25.50 inches diameter, utilizing graphite fibers. The process utilized U. S. Polymeric Inc. prepreg tape which consists of Fortafil® 4-R fibers in the E-759 epoxy resin matrix. This fabrication effort demonstrated an ability to fabricate high quality graphite/epoxy rocket motor cases in the 26.25 inch by 25.50 inch size range.

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SUMMARY

The Brunswick Corporation, under prior contract from Jet Propulsion Laboratories, fabricated a filament-wound rocket motor case which utilized graphite fibers embedded in an epoxy matrix as the reinforcement material. The details of that effort are described in Reference 1.

The object of the program described herein was to optimize the fabrication of two additional filament-wound rocket motor cases by incorporating the recommendations resulting from the previous program. Since many aspects of the manufacturing plan remained identical to the first motor case, only the departures from the original fabrication plan are described herein.

A summary of the departures from the previous fabrication plan are as follows:

1. The material system selected consisted of Great Lakes Carbon Corporation's Fortafil® 4-R fibers impregnated with U. S. Polymeric's E-759 resin system.

2. The slip angle was decreased from a critical 13.5° to approximately 8°.

3. The winding band consisted of three tapes combined into a 0.435 inch total tape width.

4. Two polar layers and two hoop layers were used, with both hoop layers external to the polar layers.

5. The target wind tensions were 4 to 4-1/2 pounds per tape for the polar layers and 4-1/2 and 5 pounds for the first and second hoop layers respectively.

6. Since the polar wind tension was decreased, it was possible to greatly simplify the tensioning and delivery system. The graphite packages were installed at the pay-off end of the longo winding arm of the polar winding machine. The desired tension levels to give adequate compaction were achieved by tensioning the package, thus eliminating many intermediate delivery system components which would have been required to achieve higher wind tensions.

7. The skirt consisted of graphite broadgoods and hoop wraps, and was fabricated in place. This precluded the shrink tape from being applied to the forward dome during the high temperature

curing cycle. An intermediate B-stage of the domes using shrink tape, therefore, was employed to enhance the compaction in the dome region.

8. A removable thread protector was placed over the forward boss to ensure that the composite buildup would not obstruct the threads.

As a result of the above modifications, the visual appearance of the rocket motor cases improved markedly over that of the earlier rocket motor case. The decrease in number of tapes from four to three greatly facilitated the winding operation as the delivery system was simplified. Experience was gained in sizing the mandrel to account for dimensional changes following washout. The Brunswick Corporation has demonstrated that high quality graphite/epoxy filament-wound structures can be fabr.cated utilizing commercially supplied pre-preg graphite tapes.

SECTION 1

INTRODUCTION

The Brunswick Corporation has demonstrated the feasibility of fabricating a rocket motor case from graphite/epoxy as described in Reference 1. The Brunswick Corporation was contracted by JPL to fabricate two additional graphite/epoxy rocket motor cases (Figures 1 and 2) in accordance with JPL Drawing No. 10049873 B. This work incorporated many of the design and fabrication recommendations which were established during previous graphite/epoxy filament winding.

This Final Report presents; (i) the fabrication procedures employed by Brunswick in building the graphite/epoxy rocket motor cases, (ii) inspection data accumulated for the two rocket motor cases, (iii) a revised stress analysis, (iv) further recommended changes to fabrication procedures and material specifications, and (v) the results of a processing evaluation study which utilized subscale pressure vessels, included as an appendix to the report.

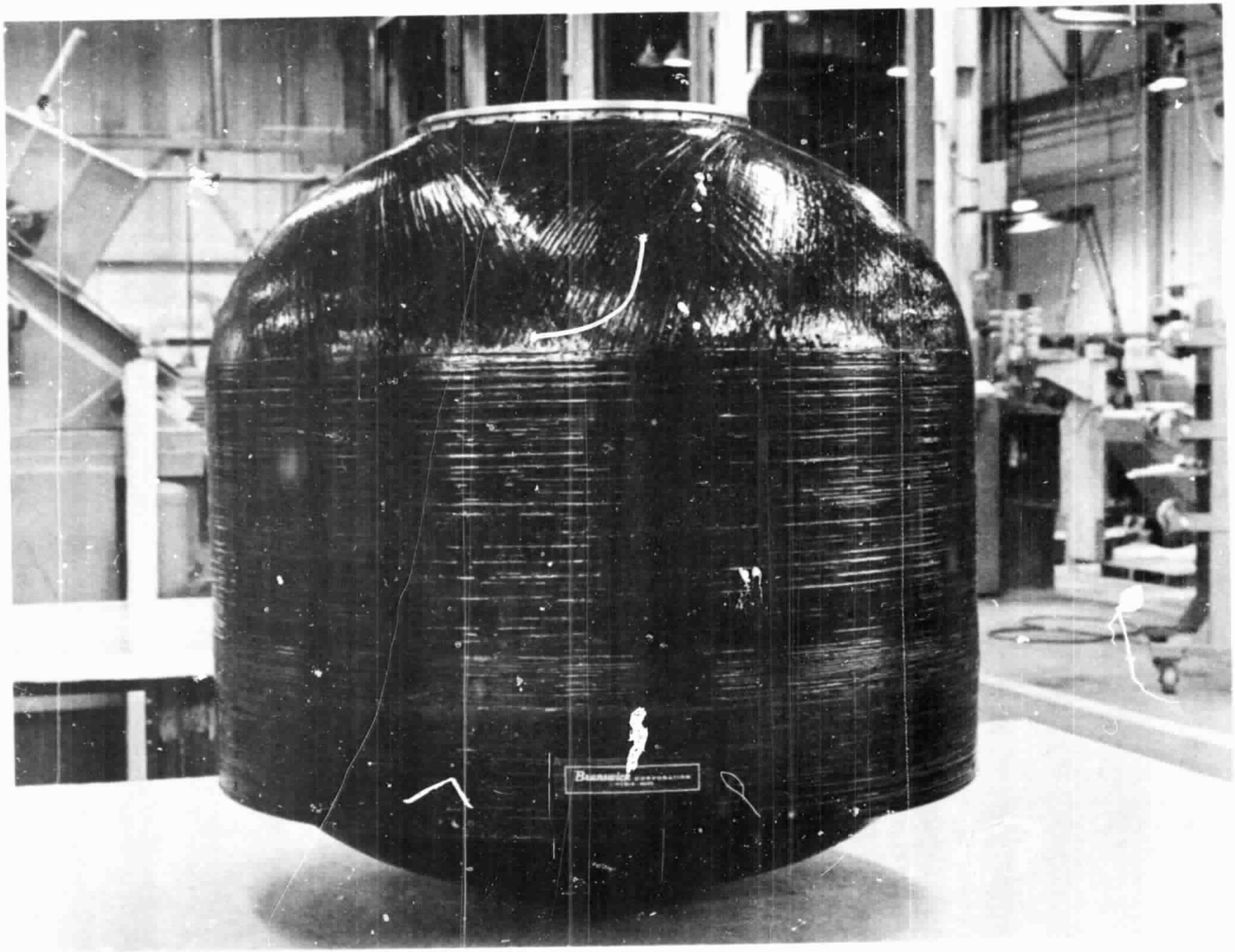

Figure 1

Rocket Motor Case S/N 001

Figure 2

Rocket Motor Case S/N 002

SECTION 2

TECHNICAL DISCUSSION

2.1 FABRICATION

The following paragraphs describe the manufacturing sequence for the two motor cases fabricated under this contract. If a particular operation was common to both rocket motor cases, no distinction is made regarding the serial numbers of the motor cases. The order of serial number coincides with the order in which the motor cases were fabricated: S/N 001 was fabricated first, followed by S/N 002. The manufacturing sequence is depicted in Figure 3.

2.1.1 Inspect and Accept Bosses

Each boss was serialized and complete documentation of boss characteristics (including weight) was recorded and retained as a permanent record. All bosses conformed to JPL drawings and Brunswick's Material Specifications.

During handling, the aft boss for use on the second motor case (S/N 002) was dropped. A small section was broken from the periphery of the boss flange. The broken section was approximately 0.185 inches wide and extended for approximately 2-1/2 inches along the outside periphery. In order to salvage the boss for use in the motor case, the following operations were performed:

(1) The damaged area underwent X-ray inspection.

(2) The boss was subjected to a dye penetrant inspection.

(3) The damaged area was polished to remove all sharp edges.

(4) The boss was heat treated to the T73 condition by heating to 350° F for 8 hours.

(5) The aft boss was dimensionally inspected following heat treatment.

(6) A final dye penetrant inspection was performed.

The above corrective action was coordinated with JPL personnel. The X-ray and dye penetrant inspection results were analyzed and the boss was determined to be suitable for its intended use.

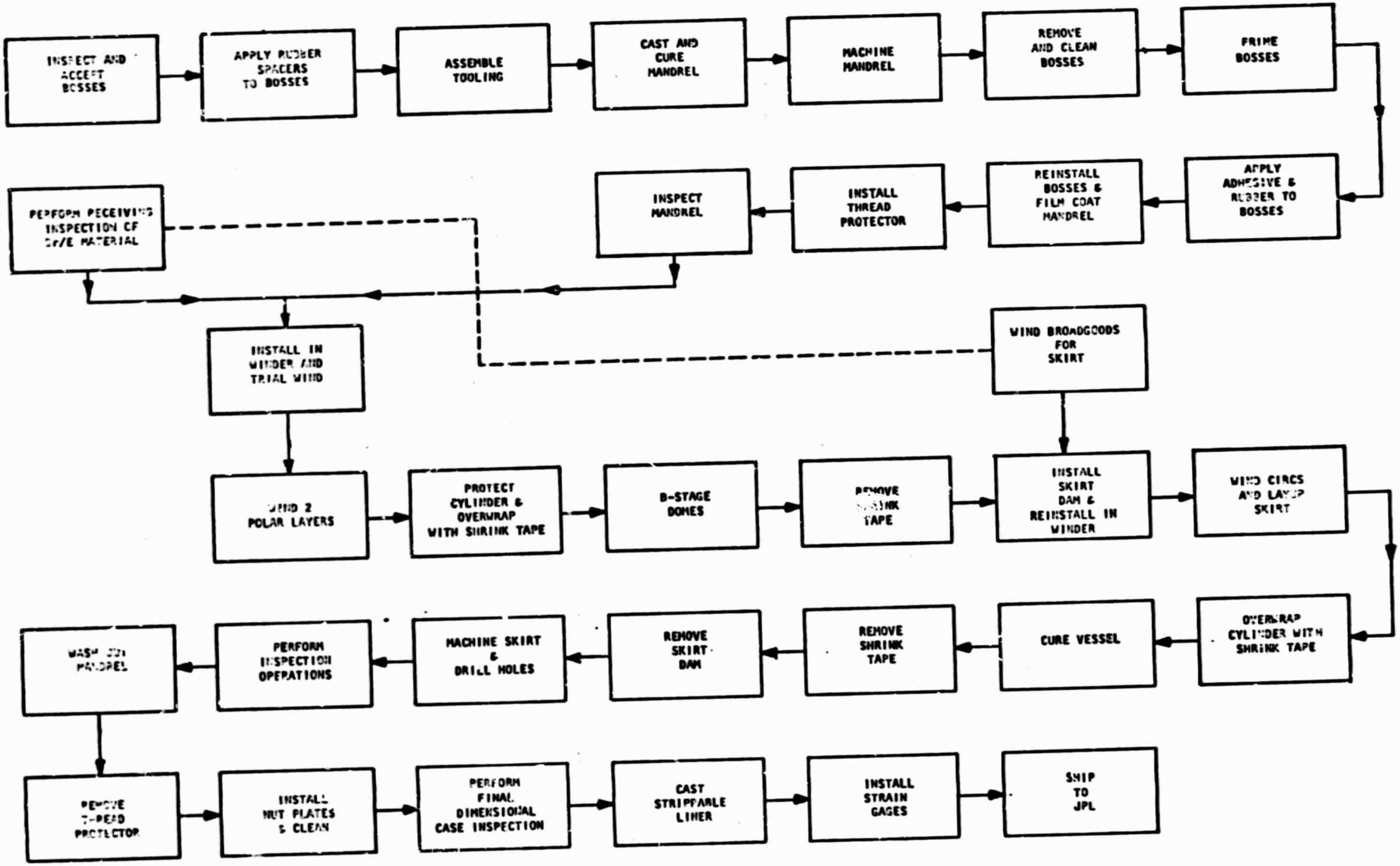

Figure 3

Manufacturing Flow Diagram

2.1.2 Apply Rubber Spacers to Bosses

Temporary rubber spacers, 0.015 inch thick, were bonded to the recessed faces of both polar bosses to provide gage point reference surfaces for machining the dome contours.

2.1.3 Assemble Tooling

The wind axis, bosses, and adaptors were assembled and inspected to verify the dimensional locations of the bosses as specified on JPL drawing 10049873 B.

For the first motor case (S/N 001), the overall length specified on the drawing was maintained. Final inspection revealed that the motor case had increased in length following mandrel removal. (See inspection data.) On the second motor case (S/N 002), a 0.076-inch thick spacer was placed beneath the forward adaptor to shorten the boss face-to-boss face distance and compensate for the increase in length. Since the dome contours were controlled by machining templates, this measure had the effect of decreasing the cylinder length.

A wire mesh cage was constructed around the wind axis assembly to add reinforcement to the cast mandrel. No means of internally heating the mandrel was used as was reported in Reference [illegible].

The entire wind axis assembly was then assembled into a mandrel mold which consisted of a 29.25-inch diameter pipe into which a sheet metal sleeve and top and bottom locating spiders had been placed.

2.1.4 Cast and Cure Mandrel

A sand mixture with a water-soluble binder matrix was prepared for casting. The cylindrical mold was filled with the sand mixture, moisture probes were installed, and a vacuum bag was installed over the open end of the mandrel to enhance moisture removal during sand curing. (Moisture probes were cast into the sand to monitor the duration of cure required.) The sand mandrel was cured at 325° F until the moisture probes indicated the required moisture content compatible with maximum mandrel properties. A vacuum of 5 to 10 inches of mercury was maintained throughout the duration of the cure.

2.1.5 Machine Mandrel

Following mandrel cure, the tooling was removed and the cylinder machined to size in a horizontal lathe. The dome ends were machined to the proper contours with tracer attachments using the boss flanges and the cylindrical section for reference.

2.1.6 Remove and Clean Bosses

Both bosses were removed from the assembly and the temporary rubber shear plies were then removed. The bosses were then cleaned for permanent rubber shear ply installation. Greater detail on the cleaning of the bosses is reported in Reference 1.

2.1.7 Apply Primer and Adhesive to Bosses

The priming and adhesive system consisted of Chemlok 205 (primer) and 220 (adhesive). Both were diluted with Toluene (one part Toluene to two parts primer and one part Toluene to two parts adhesive) and then a single layer was brush-coated on the bonding surfaces of both bosses. Both bosses were air-dried for 30 minutes prior to oven bake of 20 minutes at 160° F.

2.1.8 Apply Rubber to Bosses

Uncured rubber (V-45) was applied to the primed bosses. The rubber extended approximately one-quarter inch beyond the edge of the bosses. This excess ensured adequate fill as the rubber flowed during the high temperature curing cycle. A plastic film was placed over the uncured rubber for protection during all trial winding and handling operations. An extended period of time elapsed from the time the bosses for motor case S/N 001 were prepared and a suitable graphite material was available. (Refer to paragraph 2.1.12, "Perform Receiving Inspection of Graphite/Epoxy Materials".) Both bosses were, therefore, recleaned and prepared a second time prior to the winding operation of motor case S/N 001.

2.1.9 Reinstall Bosses and Film-Coat Mandrel

The polar bosses were reinstalled on the sand mandrel. Small cracks in the mandrel surface were filled with a room-temperature curing epoxy resin system and the entire surface was made smooth. All exposed sand was then covered with Teflon tape applied in a butt-joint manner to provide no regions of double thickness.

2.1.10 Install Thread Protector

A simple aluminum ring was threaded on the forward boss to serve as a winding dam for the composite in this region. The ring for use on motor case S/N 001 did not extend to the top of the boss flange and thus permitted resin to penetrate into the area of thread engagement requiring it to be destructively removed. The ring for use on motor case S/N 002 did extend to the top of the boss flange and had a longer taper to aid in removal. Prior to winding, the external surface of both rings were covered with a layer of Teflon tape and spray mold release agent.

2.1.11 Inspect Mandrel

Before installation in the winder, the mandrel was inspected to verify that the cylinder diameter, overall length (boss face-to-boss face), and dome contours were within the specified tolerances.

2.1.12 Perform Receiving Inspection of Graphite/Epoxy Materials

Prior to winding, graphite tape materials were evaluated for acceptability. Graphite tape was initially supplied by the Ferro Corporation. This tape consisted of Courtaulds HTS fibers impregnated with the Ferro E-350 resin system. Subscale pressure vessel and N.O.L. ring testing of this material disclosed that the tensile strength was not in compliance with the requirements of JPL Specification BS 504230C. The results of the subscale pressure vessel evaluation are included in the appendix. Brunswick requested that Ferro Corporation perform tensile tests of the material according to the procedure specified in BS 504230C. Ferro Corporation reported an average tensile strength of 166,000 psi which is well below the strength requirement of 180,000 psi average tensile strength with an individual low of 165,000 psi. Brunswick obtained JPL concurrence in the rejection of this lot of material and alternate material systems were investigated. Great Lakes Carbon Corporation's Fortafil® 4-R graphite and U. S. Polymeric's E-759 resin system was selected based on reported strength values, price, and availability. This material was required to meet the uncured physical and cured mechanical property requirements of BS 504230C with the following exceptions:

(i) the limitation to the two resin systems specified was removed,

(ii) good strength retention at 300° F (50% in shear, 75% in flexure strength of the room temperature values) was required, and

(iii) provision for a slight reduction in tensile modulus was allowed, (dependent upon the values of moduli of graphite fibers available).

Results of the testing performed by U. S. Polymeric on the lot of material used in the motor case fabrication is as follows:

	Measured	Required
Resin Solid Content	38.6%	37 ± 3%
Volatile Content	2.47%	3% max.
Flat (unidirectional) Laminate		
Flexural Strength @ R.T.	256.6 KSI	200.0 KSI
Flexural Strength @ 250° F.	255.5 KSI	170.0 KSI
Flexural Modulus @ R.T.	20.9 MSI	17.5 MSI
Flexural Modulus @ 250° F.	21.2 MSI	--
Tensile Strength @ R.T.	143.6 KSI	
Tensile Modulus @ R.T.	21.3 MSI	
Horizontal Shear Strength @ R.T.	15.5 KSI	
Horizontal Shear Strength @ 250° F.	11.6 KSI	

2.1.13 Install in Winder and Trial Wind

Initially the mandrel was installed in the winding machine, and trial winding was attempted with four individually-mounted tape packages. This arrangement was similar to that described in Reference 1 and is depicted in Figure 4. A band width of 0.595 inch at the pay-off roller was desired with this arrangement. Although considerable time was spent in attempting to achieve a gap-free pattern, an acceptable pattern could not be achieved. Several interrelated factors contributed to the winding difficulty. The many contact points and the requirement of changing the tape direction three times exaggerated the tendency for roping and necking down of the prepreg tape, resulting in excessive gapping of the wind pattern. The excessive tack of the prepreg tape increased the tendency of roping and sticking to rollers which introduced inconsistencies into the wind pattern. Also, the temperature of the winding area could not be lowered sufficiently to reduce the tack of the prepreg. Solutions to these difficulties were sought. In order to improve the quality of the wind pattern, one tape package was removed from the delivery system and the total band width was reduced to 0.404 inch. After consulting with the tape manufacturer regarding recommendations for reducing the tack of the prepreg material, both cooling the packages and extracting volatiles were attempted.

Cooling was accomplished by placing the tape packages in a 40° F cooler overnight and winding immediately upon removal from the cool storage. Because of the large surface area and low mass, it was found that the tape packages would reach room temperature after approximately one-fourth hour, which did not provide sufficient winding time. Extraction of volatiles was accomplished by placing the tape packages in a vacuum chamber overnight, prior to utilization. This measure did result in a slight improvement in the tack characteristics. Following these attempts at improving the quality of the wind pattern, the pattern was still deemed unacceptable for optimum performance.

It had been determined prior to full-scale winding that polar wind tensions of four to four and one-half pounds were adequate to give proper compaction and narrowing of the tape. Because these tensions were reduced from the initial eight pounds used in the preceding program, the decision was made to attempt applying the tension to the package directly, thus eliminating the many intermediate delivery system components required to increase the tension in a stepwise manner. The three tape packages were mounted at the head of the longo winding arm thus greatly reducing the length of the delivery system and the requirement of any directional changes (Figure 5). A band width of 0.450 inch was achieved with this arrangement, which corresponds to a narrowing of each band from its 0.200 inch width to 0.150 inch at its application onto the mandrel. An acceptable wind pattern was achieved with this arrangement.

For the winding of the second rocket motor case, a minimum amount of trial winding was required as the delivery system was unaltered following the winding of the first rocket motor case.

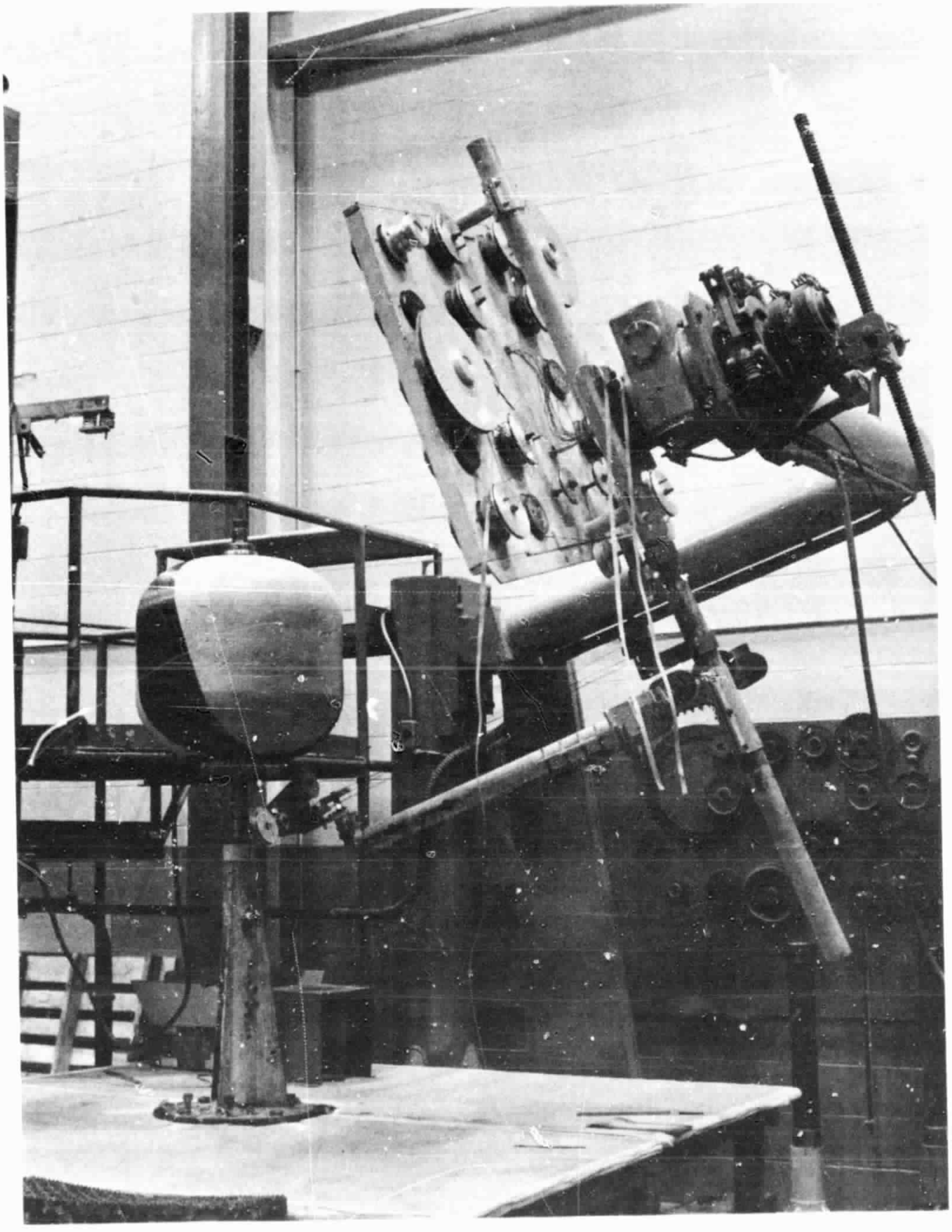

Figure 4

Plate Mounted Tensioning and Delivery System

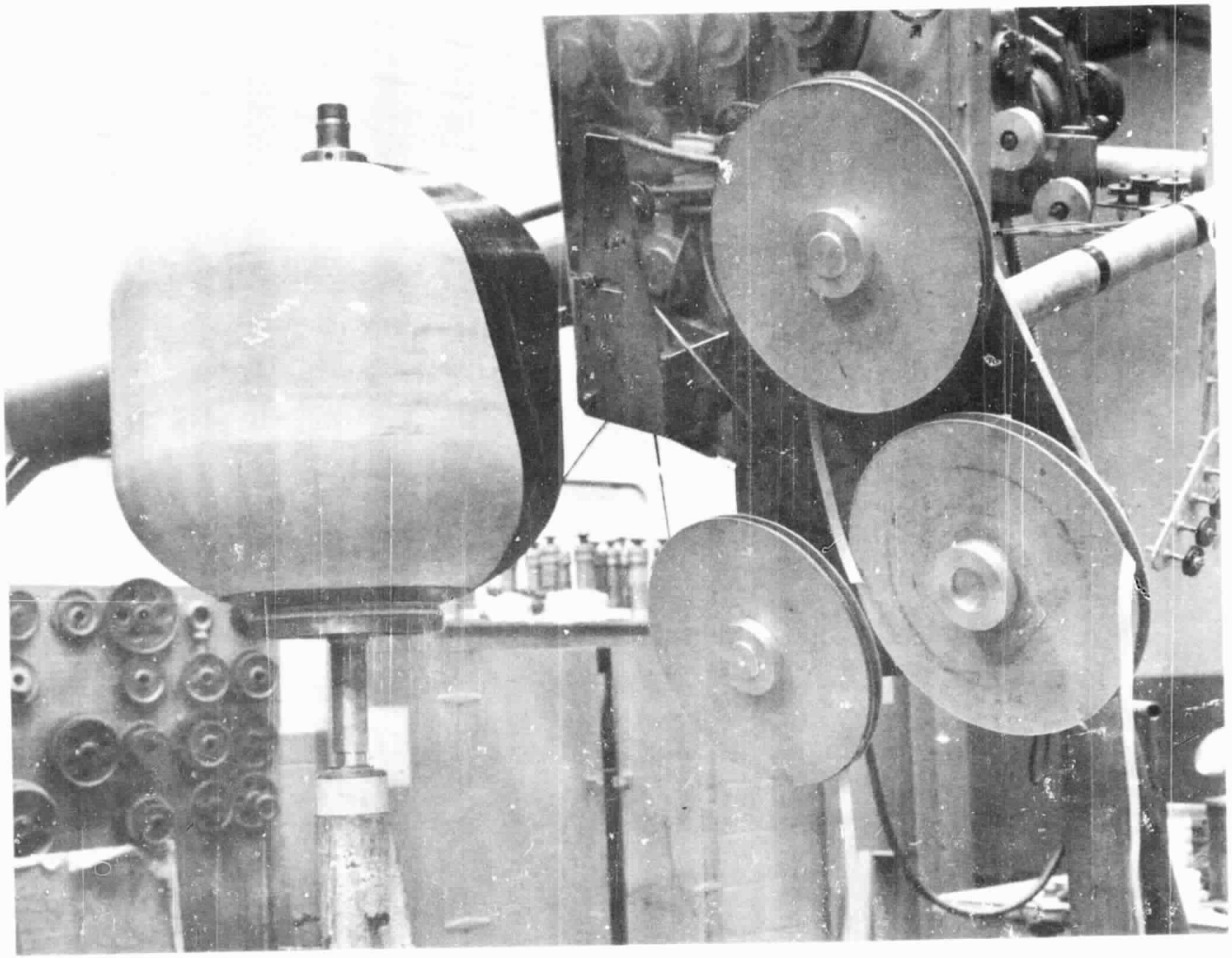

Figure 5

Head Mounted Tensioning and Delivery System

2.1.14 Wind Two Polar Layers

After the wind pattern was established during the trial winding operation performed on motor case S/N 001, the polar winding operation was straight forward (Figure 6). It was not necessary to advance the pre-preg tapes to decrease the tack. At approximately eight radial locations per each 180 degrees of mandrel rotation, short sections of tape (approximately two feet long) were hand-laid into any visible gaps on the mandrel. During the winding of motor case S/N 002, the center core of one tape package had slipped and the package was replaced. Other instances of less severe slippage within packages may have contributed to the occurrence of shingling on the forward dome of S/N 002 (Figure 7).

2.1.15 Protect Cylinder and Overwrap with Shrink Tape

Following the winding of the two polar layers, shrink tape was applied to the entire structure in a polar mode at a slight unmeasured tension. The cylinder section of each motor case was then protected from heat by overwrapping with two plies of dry fiberglass followed by one layer of asbestos cloth to inhibit resin advancement in the cylinder section. Insulated thermocouples were installed on the forward and aft domes approximately half way between the tangent and boss on the shrink tape covered surface.

2.1.16 B-Stage Domes

Each motor case was subjected to the following oven temperature cycle:

(1) Preheat oven to 200° F.

(2) Place the rocket motor case in oven.

(3) Immediately raise temperature of oven to 265 ± 5° F.

(4) Turn off heat when thermocouples installed on domes midway between bosses and tangent lines reach 250° F or 4 hours maximum time in oven.

(5) Allow chamber to remain in oven for 5 to 10 minutes after these thermocouples reach 250° F or if 4 hours are required, remove chamber immediately.

In both instances the motor case was removed from the oven at the end of four hours at which time the thermocouples measured 236° F (typical).

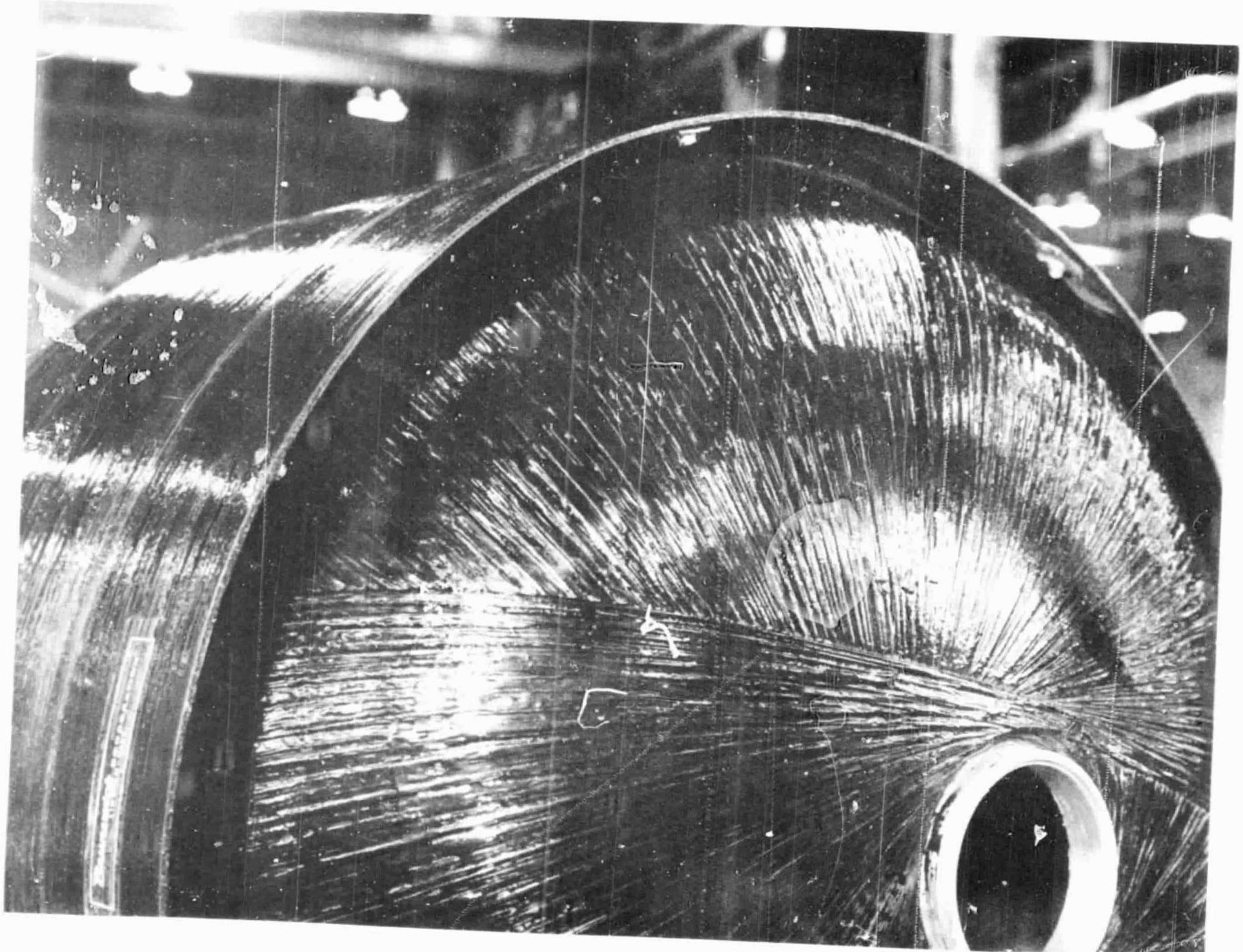

Figure 6

Forward Dome of S/N 001

Figure 7

Forward Dome of S/N 002

2.1.17 Remove Shrink Tape

Following the dome B-staging operation, the thermocouples, protective overwraps, and shrink tape were removed from the vessel.

2.1.18 Wind Skirt Broadgoods

Prior to the skirt fabrication, broadgood sheets were wound for use in the skirt lay-up operation. The broadgood sheets were cut with fiber orientations of 0° and 45° from the longitudinal case centerline. The broadgood sheets were wound in a lathe with one tape of graphite on a 15-inch diameter wood mandrel. The lead rate for the broadgood sheets for S/N 001 was 0.100 inch which resulted in each broadgood sheet having a ply thickness of approximately 0.011 inch. The broadgood sheets for S/N 002 was wound with the lead rate increased to 0.141 inch and the ply thickness decreased accordingly to approximately 0.008 inch. This lower band density accounts for some of the weight decrease apparent in motor case S/N 002.

2.1.19 Install Skirt Dam and Reinstall in Winder

Prior to skirt dam installation, the surface of the dam was cleaned and sprayed with a mold release agent. Teflon tape was applied to the inside surface of the skirt dam to (i) provide a filler between the case wall and skirt dam edge, and (ii) provide a cushioned surface.

2.1.20 Wind Circs and Lay-up Skirt

Prior to skirt fabrication, the region of the Y-joint was made flush by filling with uncured rubber (V-45). Besides serving as a filler, this rubber shear ply provides dampening of the peak shear stresses which are developed during case pressurization and skirt loading. The first layer of circ wraps was applied at a lead rate of 0.133 inches (7.5 turns/inch). The wind was started and terminated at the trim edge of the skirt dam. The plies of broadgoods were laid-up by hand with butt joints (Figure 8). Following the installation of the fourth and eighth plies of broadgoods, the skirt portion was compacted by overwrapping with shrink tape applied at hand tension. The tape was applied with a 50 per cent overlap and two passes were made. The shrink tape was then shrunk by heating with a heat gun and removed. Finally, the external hoop layer was wound.

A single tension level was used for both circ layers. The target tension value was 4-1/2 to 5 pounds; however, because of slippage within the package, the actual tension measured at the completion of the circ winding on motor case S/N 002 was 12 to 13 pounds. In this instance the tension was initially set with the package in a slippage condition and when it would not slip the tension exceeded the desirable level. No deviations to the wind tension were observed during the circ winding of the first rocket motor case, S/N 001.

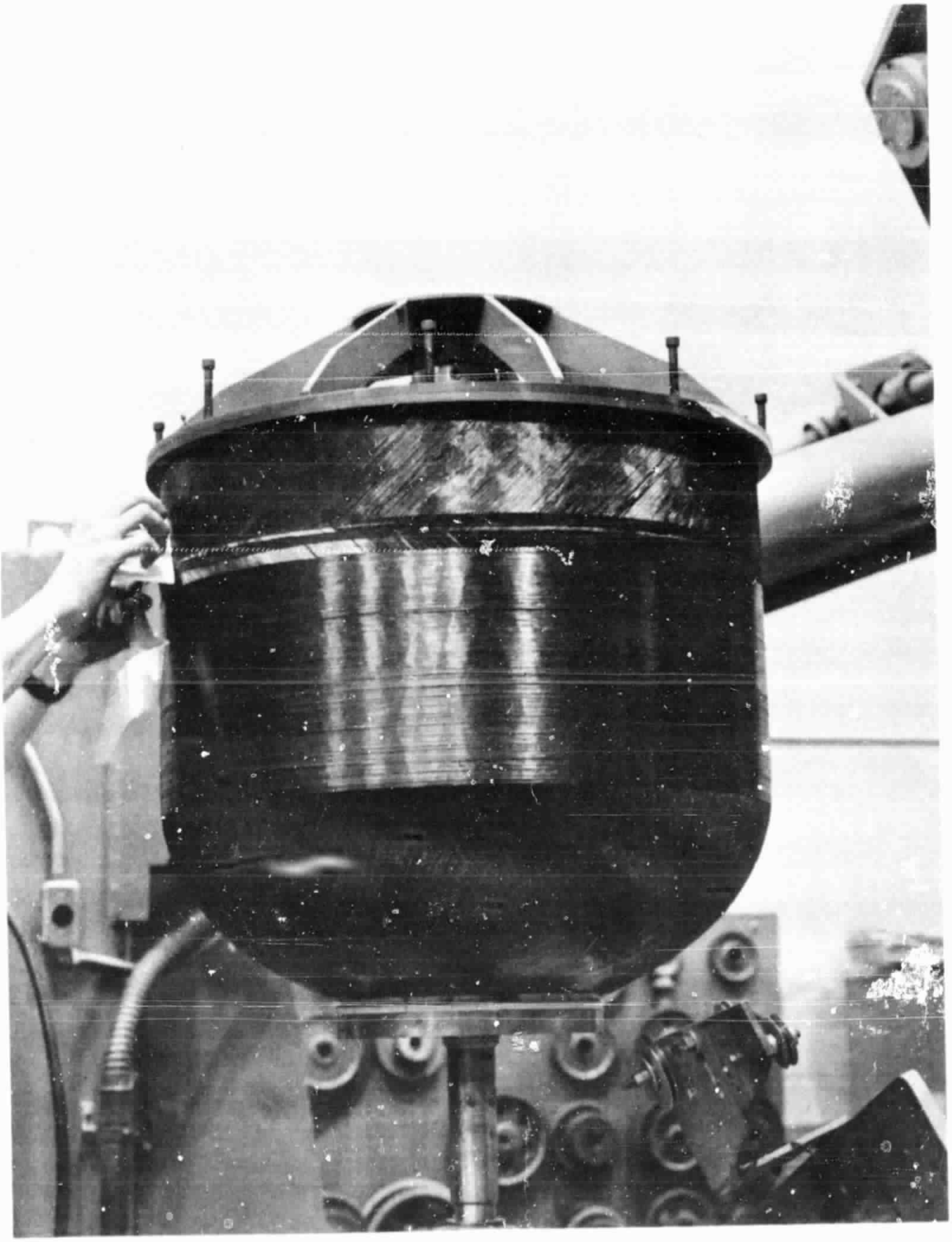

Figure 8

Skirt Lay-Up

2.1.21 Overwrap Cylinder and Skirt with Shrink Tape

The cylindrical regions of the motor cases were overwrapped with shrink tape. The shrink tape extended approximately 1-1/2 inches beyond the circ reversal location near the aft dome-cylinder tangent line. Prior to shrink tape application, the cylindrical region of motor case S/N 002 was covered with brown Teflon cloth which was carefully butt-jointed. The cloth allowed the surface resin to be absorbed.

2.1.22 Cure Vessel

A different cure cycle was used for each motor case. For motor case S/N 001 the oven temperature was maintained within the following limits:

A. Preheat oven to 150° F.
B. Raise oven temperature to 225° F in 1/2 hour.
C. Maintain oven temperature at 225 ± 10° F for 2 hours.
D. Raise oven temperature to 350° F in 3 to 5 hours.
E. Maintain oven temperature at 350 ± 5° F for 2 hours.
F. Set oven at 255° F for 1-1/2 hours.
G. Set oven at 200° F for 1-1/2 hours.
H. Turn off oven; keep doors closed for 1-1/2 hours.
I. Open doors and do not remove motor case from oven until. surface temperature measured with a pyrometer reaches 200° F.

As the maximum temperature of the motor case measured throughout the duration of the above cure was 316° F, an alternate cure was used for motor case S/N 002. As the motor case must be subjected to severe temperature requirements, it was desirous that the composite be exposed to the 350° F temperature during cure. For motor case S/N 002, the actual thermocouple indication of part temperature was maintained within the same specified limits as used for monitoring the oven temperatures during the cure of motor case S/N 001. In addition, the time at maximum temperature was extended an additional two hours. The thermocouple readings recorded for each motor case are presented in Figures 9 and 10. The thermocouple locations were all at mid-cylinder.

2.1.23 Finishing Operations

After the assembly cooled to room temperature, all thermocouples and shrink tape were removed. The skirt dam was removed by jacking the dam with cap screws at the skirt edge. The motor cases were installed in the lathe and the skirts were trimmed to length and the nut plate holes drilled. Inspection operations requiring the motor case to be supported between centers were performed at this time. These data are included in Tables I and II.

Washout was accomplished by placing each motor case and mandrel assembly on a washout stand consisting of a table with a circular opening. The assembly rested on the skirt with the aft boss up. Warm water was directed into the exposed sand and the sand was allowed to soften sufficiently to permit removal of the wind axis and polar boss adaptors. Warm water was than circulated through the exposed sand until all sand was removed. The wire mesh was then removed by hand. The time required to completely remove all portions of the mandrel from motor case S/N 001 was approximately one week. The fact that the first mandrel was stored several months accounts for the excessive amount of time required. The time required to completely remove the mandrel from motor case S/N 002 was 4 hours.

Following mandrel removal, the motor cases were cleaned and the thread protectors were removed The thread protector used on motor case S/N 001 had to be destructively removed as resin had penetrated into the area of thread engagement.

Nut plates were installed and the motor cases were then final inspected. The inspection data for each motor case is included in Tables I and II. A breakdown of the component weights for each rocket motor case is included in Table III.

Prior to shipment of the motor cases to JPL, strippable elastomeric liners and strain gages were installed. The liner material was TURCO 5145 chem mill maskant. For motor case S/N 001, the liner was slosh-coated and for motor case S/N 002, the liner was sprayed.

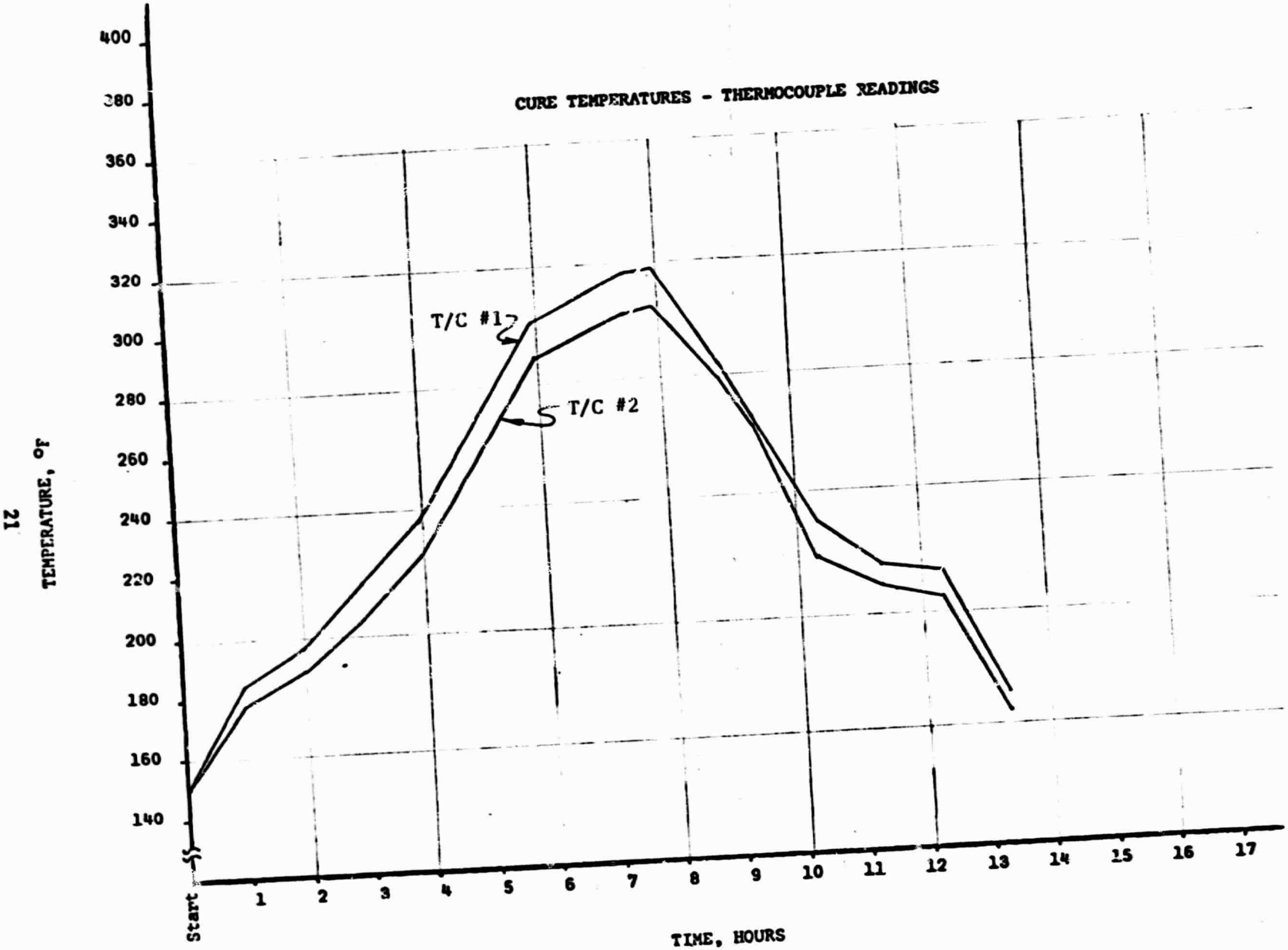

Figure 9
Cure Temperature Chart - S/N 001

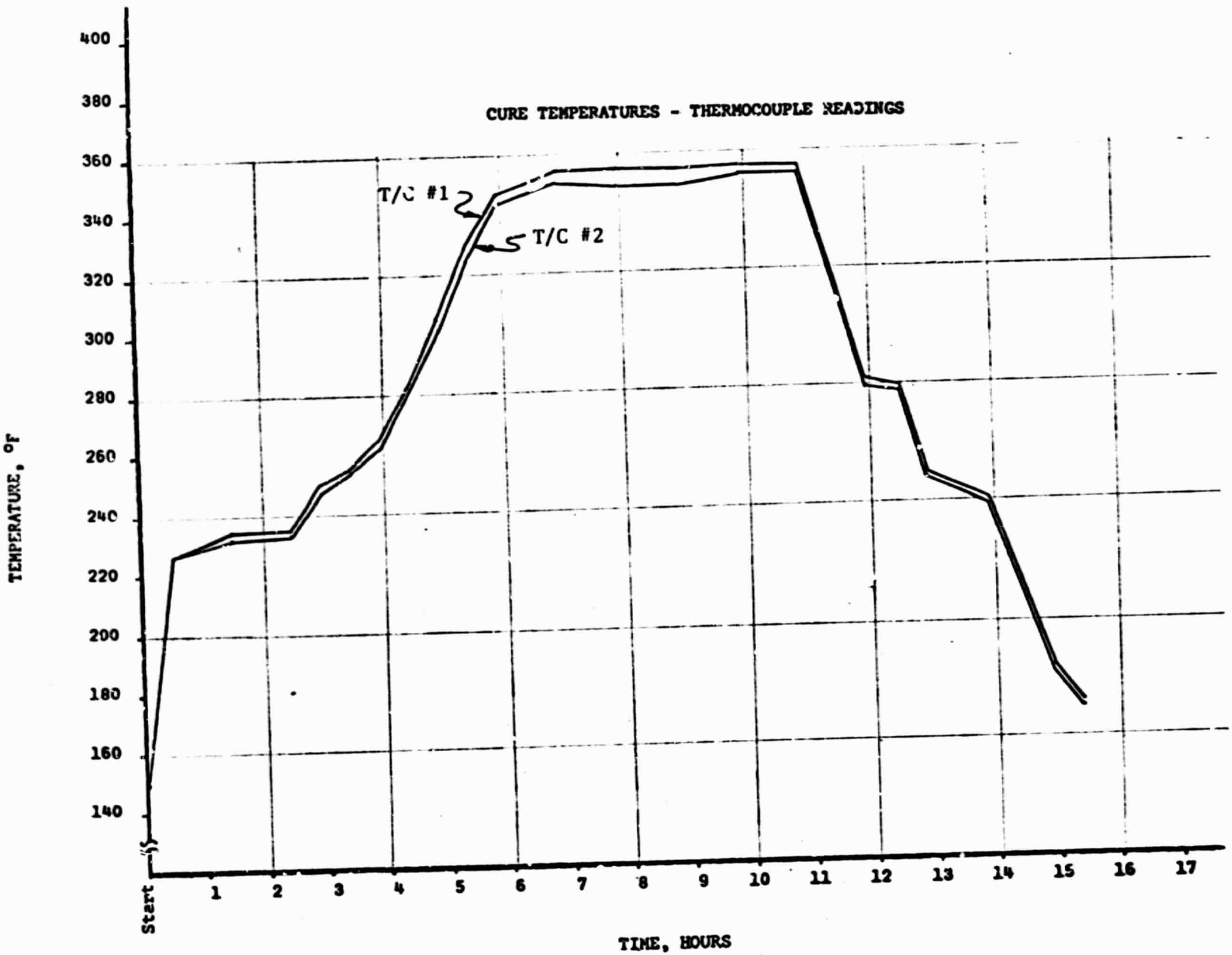

Figure 10
Cure Temperature Chart - S/N 002

TABLE I

S/N 001

Description	Drawing Dimension & Tolerance	Actual
Overall Length (in.)	26.25 ± .030	26.326
Skirt/Boss 4 places Record Min/Max (in.)	4.15 ± .030	4.213 4.243
Weight to nearest .1 pound	Record	11.88
Outside Diameter at 9.88" Fwd of Aft Boss (in.)	Record	25.678
Outside Diameter at 12.88" Fwd of Aft Boss (in.)	Record	25.678
Outside Diameter at 16.88" Fwd of Aft Boss (in.)	Record	25.665
Outside Diameter at 1/2" Aft of Stub Skirt Trim (in.)	Record	25.625
Inside Diameter at 9.88" Fwd of Aft Boss (in.)	25.48 ± .030	25.525
Inside Diameter at 12.88" Fwd of Aft Boss (in.)	25.48 ± .030	25.525
Inside Diameter at 16.88" Fwd of Aft Boss (in.)	25.48 ± .030	25.522
Skirt Thickness (Min/Max) (in.)	.064 ± .010	.105 .115
Skirt I.D. (Min/Max) (in.)	25.39 ± .030	25.415 25.395
Aft Boss Face to Hoop Termination (in.)	7.92 ± .120	8.006
TIR Skirt Stub I.D. (in.)	.020	.028
TIR Skirt Trim (in.)	.015	.003

TABLE II

S/N 002

Description	Drawing Dimension & Tolerance	Actual
Overall Length (in.)	26.25 ± .030	26.286 26.295
Skirt/Boss 4 places Record Min/Max (in.)	4.15 ± .030	4.235 4.262
Weight to nearest .1 pound	Record	11.53
Outside Diameter at 9.88" Fwd of Aft Boss (in.)	Record	25.585
Outside Diameter at 12.88" Fwd of Aft Boss (in.)	Record	25.584
Outside Diameter at 16.88" Fwd of Aft Boss (in.)	Record	25.584
Outside Diameter at 1/2" Aft of Stub Skirt Trim (in.)	Record	25.586
Inside Diameter at 9.88" Fwd of Aft Boss (in.)	25.48 ± .030	25.487
Inside Diameter at 12.88" Fwd of Aft Boss (in.)	25.48 ± .030	25.499
Inside Diameter at 16.88" Fwd of Aft Boss (in.)	25.48 ± .030	25.463
Skirt Thickness (Min/Max) (in.)	.064 ± .010	.089 .098
Skirt I.D. (Min/Max) (in.)	25.39 ± .030	25.404
Aft Boss Face to Hoop Termination (in.)	7.92 ± .120	7.694
TIR Skirt Stub I.D. (in.)	.020	.020
TIR Skirt Trim (in.)	.015	.003

TABLE III

COMPONENT WEIGHTS (lbs)

	S/N 001	S/N 002
Composite	8.07	7.75
Forward Boss	.51	.51
Aft Boss	2.67	2.64
Rubber*	.55	.55
Nut Plates and Rivets	.08	.08
Total	11.88	11.53

*Calculated

2.2 STRESS ANALYSIS

A netting analysis of the "as-wound" configuration follows. All values required for use in the analysis are common to both rocket motor cases. The values of yield and density were obtained from Reference 2.

The area/tape is:

$$\text{area/tape} = \frac{1}{(\text{yield})\ (\text{density})} \qquad \text{(Cross-sectional Fiber Area)} \tag{1}$$

where yield = 2600 ft/lb

and density = .065 lb/cu in

then

$$\text{area/tape} = \frac{1}{(2600\ \text{ft/lb})\ (.065\ \text{lb/cu in})\ (12\ \text{in/ft})} \tag{2}$$

$$= .493 \times 10^{-3}\ \text{in}^2 \qquad \text{(Cross-sectional Fiber Area)}$$

Polar fiber thickness is:

$$t_{f\alpha} = \frac{(\text{no. of tapes})\ (\text{no. of plies})\ (\text{area/tape})}{(\text{band width})} \tag{3}$$

$$= \frac{(3\ \text{tapes})\ (4\ \text{plies})\ (.493 \times 10^{-3}\ \text{in}^2/\text{tape})}{(.435\ \text{in.})} \tag{4}$$

$$t_{f\alpha} = .0136\ \text{inch}$$

Hoop fiber thickness is:

$$t_{f\theta} = (\text{no. of tapes})\ (\text{no. of plies})\ (\text{area/tape})\ (\text{turns/in.}) \tag{5}$$

$$= (1\ \text{tape})\ (4\ \text{plies})\ (4.93 \times 10^{-3}\ \text{in}^2/\text{tape})\ (7.5\ \text{turns/in.}) \tag{6}$$

$$t_{f\theta} = .0148\ \text{inch}$$

The values of polar and hoop fiber thickness represent actual fiber thicknesses as they are based on the winding parameters actually used and the cross-sectional fiber area of the tape material. The measured values of average wall thickness for each motor case can be determined from the final motor case dimensions presented in Tables I and II. These average composite wall thicknesses are:

Motor Case S/N 001	.075 inch
Motor Case S/N 002	.051 inch

The difference in the thicknesses may indicate that more resin was absorbed by the bleeder cloth installed over the cylinder section of motor case S/N 002 during the curing operations. Apparent fiber volume percents for the two motor cases are 38% for S/N 001 and 56% for S/N 002.

For purposes of this analysis, the stresses at 210 psi contained pressure will be calculated. This pressure was the maximum pressure to which motor case S/N 001 was subjected during proof testing.

<u>Then fiber stresses at 210 psi contained pressure are:</u>

$$\sigma\phi_f = \frac{PR}{2\cos^2\alpha\ t_{f\alpha}} \quad \text{(Polar fiber stress)} \tag{7}$$

where P is contained pressure, psi, R is mean radius to cylinder wall, in., α is the polar wind angle, and $t_{f\alpha}$ is the polar fiber thickness, in.

$$\sigma\phi_f = \frac{(210\text{ psi})\ (12.8\text{ in})}{2\ (.945)^2\ (.0136\text{ in})} = 110{,}700\text{ psi} \tag{8}$$

and

$$\sigma\theta_f = \frac{PR}{t_{f\theta} + t_{f\alpha}\sin^2\alpha} \quad \text{(Hoop fiber stress)} \tag{9}$$

where P, R, α, and $t_{f\alpha}$ are the same as above and

$t_{f\theta}$ is the hoop fiber thickness, in.

$$\sigma\theta f = \frac{(210\text{ psi})\ (12.8\text{ in})}{.0148\text{ in.} + (.0136\text{ in})\ (.327)^2} = 165{,}400\text{ psi} \tag{10}$$

The composite allowable tensile strength reported by Great Lakes Carbon Corporation on the products data sheet for a 60 percent fiber volume unidirectional laminate is 220 ksi. Based on this value, the motor case would fail in the hoop fibers at a contained pressure of 465 psi. Experience shows that allowable strengths for pressed laminate specimens do not necessarily correlate to filament-wound structures, with the above prediction being non-conservative. Since no pressure vessel data is available and the N.O.L. ring composite tensile strength data for this material system appears to be invalid, accurate prediction of the ultimate burst pressure is difficult.

Based upon the strain gage data obtained during the proof testing of rocket motor case S/N 001, the projected ultimate burst pressure is believed to be between 350 and 420 psi. Further basis for projecting the burst pressure range to be between 350 and 420 psi is that the fiber stresses at 350 psi contained pressure would be 184,500 psi and 276,000 psi in the polar and hoop fibers respectively. During the subscale test program conducted prior to the fabrication of the previous motor case, polar and hoop fiber stresses of 220,000 psi and 310,000 psi respectively were achieved and are reported in Reference 1. These achieved stress levels at burst were obtained in a vessel which utilized the Courtaulds HTS fiber in its construction, and the reported strength of this fiber is approximately 350,000 psi as compared to 450,000 psi fiber strength for the Fortafil® 4-R fiber as reported in Reference 2.

SECTION 3

CONCLUSIONS

As a result of this program, the following conclusions have been reached by the Brunswick Corporation:

1. The changes proposed in Reference 1 were incorporated and resulted in greater ease of fabrication and improved motor case appearance. The mandrel geometry was such that no slippage was observed during the polar winding operation.

2. The delivery system was near optimum. This is largely due to the low wind tension used for wrapping the polar layers which permitted the placement of the entire delivery system at the end of the longo arm and the elimination of many intermediate delivery system components.

3. The quality of the graphite tape packages is reflected in the quality of the wound motor case. Misalignment of the tape coming off the package causes a decrease in the tape width as the tape contacts the sides of rollers within the delivery system. Future winding should incorporate high quality spools for the pre-preg tape.

4. The technique of B-staging the domes with shrink tape overwraps prior to skirt fabrication to achieve compaction in the dome regions resulted in adequate compaction. The forward domes could not be overwrapped with shrink tape during the high temperature curing cycle because the skirt dam was in place. Had it been possible to overwrap domes during cure, the appearance of these domes may have been improved. Perhaps a more optimum dome B-staging operation could have been employed. Selecting more optimum B-staging time and temperature parameters would require additional laboratory evaluation.

5. The wound-in-place graphite skirt presented no fabrication difficulties and eliminated many problems which were encountered with the bonded titanium skirt during the earlier program. These problems included dimensional and thermal mismatch between the skirt and motor case, and skirt discontinuity loads caused by the higher modulus titantium skirt.

6. The age of a sand mandrel has a pronounced effect on how readily the mandrel will soften during washout.

SECTION 4

RECOMMENDATIONS

4.1 RECOMMENDED CHANGES

Based on the experience gained during the fabrication of the two graphite/epoxy rocket motor cases under this contract, the following modifications to the procedures and specifications used are proposed:

4.1.1 Graphite Tape Packages

The graphite tape supplied for this program was packaged on cardboard spools. The cardboard sides of the packages were not rigid and, in many instances, the thin cardboard center core would separate from the package sides which made tensioning and alignment extremely difficult to control.

Any misalignment of the package on its tensioner would magnify as the tape passed through the delivery system. Future filament winding with pre-preg tapes should not be attempted with packages of the quality which were used. Material specifications for graphite/epoxy tape should specify the materials used for package components and should specify the required package thickness. The packages supplied by the Fiberite Corporation for the motor case winding reported in Reference 1 were of acceptable quality. Those packages consisted of aluminum sides which were held to the plastic core with several small screws. No instances of package separation occurred during the winding operations.

4.1.2 Skirt Machining Procedure

For the current program, the skirts were machined with the polar bosses in a restrained condition. The skirt-to-boss face dimensions were maintained until the mandrel was removed and the motor case domes "sprung" outward. In future motor case fabrication, the skirt should be machined following mandrel removal to maintain the dimensional tolerance specified on the drawing. This would, however, require additional tooling.

An alternate means of maintaining the dimension could be to machine the skirt long to compensate for the amount of dome displacement following mandrel removal. This method would require experience gained during the fabrication of several motor cases and would be subject to deviations encountered in the amount of dome displacement due to very subtle differences in motor case processing.

4.1.3 Circ Termination Location

Although the location of circ reversal is carefully controlled during the winding operation, slippage onto the dome region during final cure will alter the location. A method of limiting the amount of slippage might include the employment of a removable winding dam to hold the circs in place. An alternate means would be to reverse the circs short of the desired reversal location and anticipate the amount of slippage which will occur. This method would require experience gained during the fabrication of several motor cases.

It is believed that the occurrence of slippage will have minimal effect on overall performance. In order to eliminate a dimensional discrepancy, a practical resolution would be to specify the reversal location in the "as-wound" condition prior to final cure.

4.1.4 Definition of Tack

A technical definition of tack must be authored and incorporated into the material specifications used in the procurement of graphite/epoxy tapes. The definition must take into account the sensitivity of the tack characteristic to temperature changes.

SECTION 5

NEW TECHNOLOGY

No reportable items of new technology have been identified as a result of this program.

SECTION 6
REFERENCES

1. Humphrey, W. D., and Schmidt, W. W., Filament-Wound Graphite/Epoxy Rocket Motor Case-Fabrication Report, BC-8845-FAB, Brunswick Corporation, Lincoln, Nebraska (July 1972)

2. Technical Data Sheet on Fortafil® 4-R (CO), Great Lakes Carbon Corporation, copyright 1972

APPENDIX

SUBSCALE TEST PROGRAM

Prior to fabrication of the motor cases, six 100 cubic-inch pressure vessels were fabricated for the purpose of evaluating the following process variables;

(i) material handling characteristics and composite performance,

(ii) the effects of varying the polar band density (tows/inch/ply), and

(iii) the effect of shrink tape removal over the dome regions prior to the high temperature curing cycle.

These vessels were fabricated with the Courtaulds HTS/E-350 material which was later rejected due to insufficient tensile strength. As these vessels were fabricated with prepreg tape of unacceptable quality, the achieved performance of these vessels was not consistent with previous performance levels achieved by the Brunswick Corporation. Because these test results are influenced by the quality of the prepreg tape, the validity of drawing conclusions based on these results is seriously questioned. The test results and fabrication details for each of the vessels is included in Table IV of this report. More details of the vessel fabrication are included in Reference 1.

Oven B-staging for 250° F for 20 minutes or B-staging under heat lamps at 160 to 170° F for two hours resulted in nearly equivalent burst pressure levels. Much resin migration was present on S/N 005 indicating that the combination of time and temperature resulted in too much resin advancement. As oven B-staging for 40 minutes duplicated the burst pressure performance of the standard oven cured vessel, S/N 002, it appears oven B-staging for 20 minutes was insufficient to obtain maximum performance. B-staging with heat lamps made it possible to direct the heat onto the dome regions, thus retaining a fresher appearance of the material in the cylinder region.

The winding of two polar layers with a sparse winding band density is superior to winding a single polar layer with a dense winding band density. The effect of imperfections such as gaps and startup and termination of the wind pattern have a pronounced effect on vessel performance of a one polar layer vessel. A one polar layer motor case or pressure vessel structure should be avoided if possible, even if this means sacrificing some "theoretical" efficiency.

TABLE IV

100 CUBIC-INCH PRESSURE VESSEL DATA

Serial No.	Fabrication Details	Composite Weight	Wall Thickness	Burst Pressure
001	2 polar layers with 4 tows/in/ply, standard oven cure	109.5 gr.	.052 in.	680 psi
002	1 polar layer with 8 tows/in/ply, standard oven cure	105.5 gr.	.051 in.	540 psi
003	Same as S/N 002 except domes were B-staged in oven at 250° F for 20 minutes	107.0 gr.	.052 in.	480 psi
004	Same as S/N 002 except domes were B-staged in oven at 250° F for 40 minutes	106.5 gr.	.051 in.	550 psi
005	Same as S/N 002 except domes were B-staged with heat lamps at 200° F mininum for two hours	106.0 gr.	.087 in.	435 psi
006	Same as S/N 002 except domes were B-staged with heat lamps at 160-170° F for two hours	106.0 gr.	.059 in.	540 psi